Low-Frequency, Long-Range Sound Propagation through a Fluctuating Ocean: Analysis and Theoretical Interpretation of Existing and Future NPAL Experimental Data

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LONG-TERM GOALS

To theoretical study low-frequency, long-range sound propagation through a fluctuating ocean, including studies of 3D effects.

To compare obtained theoretical results with experimental data.

OBJECTIVES

To develop a new, modal, 3D theory of low-frequency, long-range sound propagation through an ocean with random inhomogeneities.

Based on this theory, to develop computer codes for calculating statistical moments of a sound field propagating through the ocean with internal gravity waves, internal tides, and spiciness.

To compare theoretical predictions with data obtained during the 1998 NPAL experiment and those which will be obtained during the 2004-2005 NPAL experiment.

APPROACH

Experimental and theoretical studies of low-frequency, long-range sound propagation through a fluctuating ocean are important for many practical problems, e.g. source detection and ranging, communication, and acoustic tomography. The coherence of low-frequency sound waves propagating over megameter distances diminishes noticeably due to sound scattering by internal gravity waves. As a result, the performance of large acoustic arrays degrades.

To experimentally study low-frequency, long-range sound propagation in a fluctuating ocean, the North Pacific Acoustic Laboratory (NPAL) carried out two comprehensive experiments. The first experiment was carried out in 1998-1999. A detailed description of the experiment is given in Ref. [1]. The second NPAL experiment was carried out in 2004-2005. A preliminary description of this

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14. ABSTRACT
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experiment can be found at the web cite [2]. The experiment consisted of three sub-experiments: Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), Basin Acoustic Seamount Scattering EXperiment (BASSEX), and SPICE04 experiment. Two autonomous vertical line array (VLA) receivers were used. The Shallow VLA spanned the depth from 350 m to 1750 m and consisted of 40 hydrophones, and the Deep VLA spanned the depth from 2150 m to 4270 m and consisted of 60 hydrophones. For both VLAs, the vertical spacing between hydrophones was 35 m. The horizontal distance between the Shallow and Deep VLAs was 5.4 km. The VLAs recorded low-frequency sound signals from several stationary sources located at about 500 km, 1000 km, and 2470 km from VLAs, and from a 75-Hz acoustic source suspended from the *R/V Melville*.

The main goal of the current project is analysis of the experimental data obtained during these two NPAL experiments. This analysis is done by signal processing of the experimental data, developing a 3D modal theory of sound propagation through a fluctuating ocean, and comparing experimental and theoretical results.

WORK COMPLETED

During the reporting period, the following tasks were accomplished:
Task 1. The cross-modal coherence functions of a sound wave propagating in a fluctuating ocean were calculated. The results obtained were summarized in Refs. [3,4].
Task 2. An analytical expression for the coherence function of the *n*-th acoustic mode propagating in a fluctuating ocean was obtained, see Ref. [3].
Task 3. The mean sound field in an oceanic waveguide with random inhomogeneities was calculated using the Chernov method.

RESULTS

During the reporting period the following results were obtained in accomplishing the tasks mentioned above:

Task 1.
Closed equations for the cross-modal coherence functions of a monochromatic, low-frequency sound wave propagating over long ranges in a fluctuating ocean were derived using Chernov's method. This method is similar to the Markov approximation and is based on the assumption that sound scattering by an ocean slab with a horizontal scale of the order of a correlation radius of random inhomogeneities is weak. (For sufficiently low frequencies, this assumption is valid.) Therefore, low-frequency, long-range sound propagation through a fluctuating ocean can be considered as a sequence of statistically independent events.

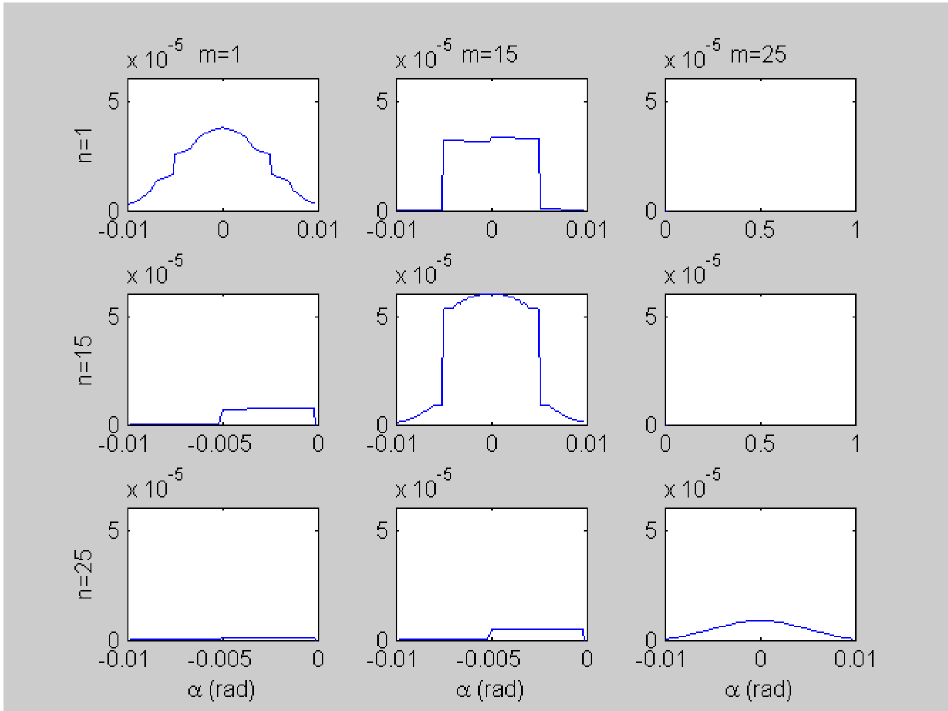

Figure 1. The cross-modal coherence functions versus the angle α characterizing direction of sound propagation in a horizontal plane. For this figure, the mode numbers n, m = 1, 15, 25 and the propagation distance x = 1000 km.

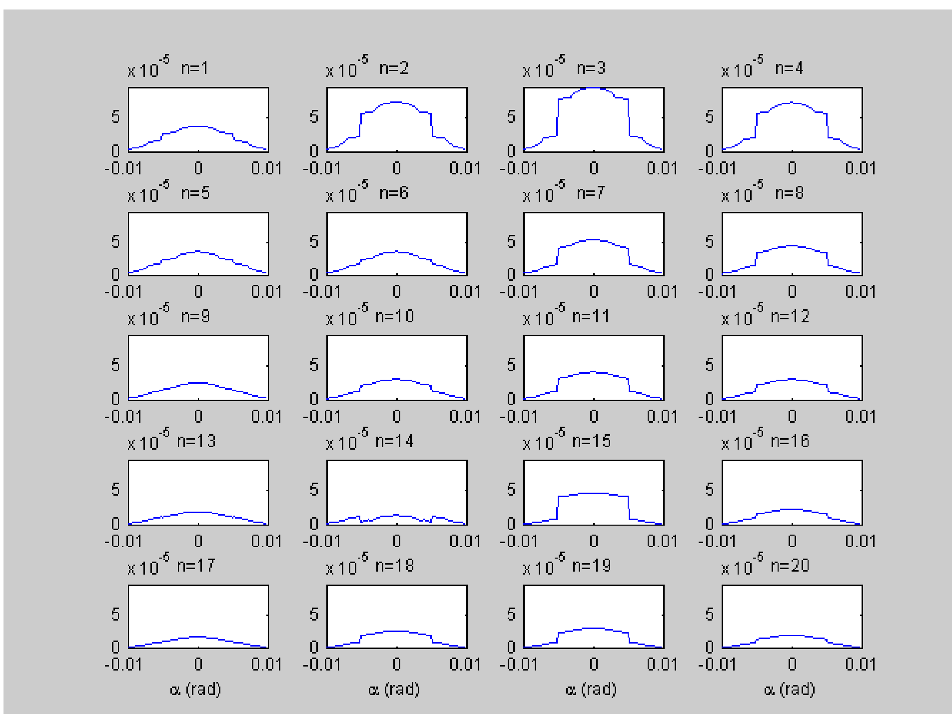

Figure 2. The coherence functions of the n-th modes versus the angle α. For this figure, n =1, 2, …20 and x = 1000 km.

The derived closed equations for the cross-modal coherence functions are involved and difficult to solve even with the use of modern computers. Therefore, these equations were simplified by assuming that the horizontal angular spectrum of the scattered sound field is narrow. (Note that this assumption is valid for the geometries of the NPAL experiments.) When simplifying the closed equations for the cross-modal coherence functions, it was ensured that acoustic energy is conserved. Then, these equations were solved numerically. The results obtained are presented in Figs. 1-2. The first of these figures shows the magnitudes (in arbitrary units) of the cross-modal coherence functions versus the angle α characterizing direction of sound propagation in a horizontal plane. (Note that the coherence functions are not normalized.) The cross-modal coherence functions were calculated for the sound propagation distance $x = 1000$ km and mode numbers $n, m = 1, 15, 25$. It follows from Fig. 1 that the cross-modal coherence is not, generally, negligible. Figure 2 shows magnitudes of the coherence functions of the first twenty modes ($n = 1,2,...20$) versus the angle α for the same propagation distance. It follows from Figs. 2 and 3 that there is significant diffusion of acoustic energy in the horizontal direction.

The closed equations derived by the Chernov method show that the cross-modal coherence functions exhibit rapid oscillations in the direction of sound propagation. Such oscillations are difficult to observe experimentally due to a finite frequency band of acoustic signals, weak intermittency of random inhomogeneities in the ocean, etc. Therefore, the closed equations for the cross-modal coherence functions were spatially averaged. Using these spatially-averaged equations, the coherence radius of the sound field was estimated for the geometry of the 1998-1999 NPAL experiment. The value of the coherence radius was found to agree with that measured during the experiment [5,7].

Task 2.
Using the spatially-averaged equations for the cross-modal coherence functions derived in Task 1, we obtained an approximate analytical expression for the coherence function of the *n*-th acoustic mode propagating in a fluctuating ocean:

$$\Gamma_n(x; y, y_+; z_1, z_2) = \frac{\xi u_n(z_1) u_n(z_2)}{x \xi_n} \exp\left(i \frac{\xi y y_+}{x} - \int_0^x H(yx'/x) dx' \right) \vec{A}(0). \qquad (1)$$

Here, z_1 and z_2 are the depths of two hydrophones, y and y_+ are the distance between the hydrophones and their geometrical center along the horizontal axis perpendicular to the direction of propagation, u_n are acoustic mode profiles, ξ_n are horizontal wavenumbers, ξ is their characteristic value, the vector $\vec{A}(0)$ characterizes the mode intensities near the source, and the matrix H is expressed in terms of the spectrum of ocean inhomogeneities. The approximate analytical solution for the coherence function Γ_n given by Eq. (1) has the following important properties. First, it conserves acoustic energy. Second, for $y = 0$, it is the exact solution of the spatially-averaged equations. Third, the coherence function Γ_n integrated over y_+ coincides with that obtained from the spatially-averaged equations also integrated over y_+. Forth, in the limiting case when only one acoustic mode is present, the coherence function $\Gamma_{n=1}$ coincides with that in a random medium without regular refraction, which was calculated in classical theories of waves in random media.

Figure 3 shows the coherence function $\Gamma_{n=10}$ (normalized by its maximum value) versus y for different values of the propagation distance x. In figure, the maximum value $y = 3000$ m corresponds to the horizontal scale of the billboard acoustic array in the 1998-1999 NPAL experiment. It follows from Fig. 3 that the horizontal coherence significantly diminishes at the propagation distances of about $x = 1000$ km. For $x = 4000$ km (the propagation distance of the 1998-1999 NPAL experiment), the horizontal coherence radius is about 600 m. This value agrees with that measured during the 1998-1999 NPAL experiment [5].

Task 3.
The mean sound field propagating in an oceanic waveguide with random inhomogeneities was calculated using the Chernov method. The mean sound field was expressed as a sum of normal modes, which attenuate exponentially. Numerical estimates showed that the characteristic attenuation distance of the
normal modes strongly depends on the mode number and, for the sound frequency $f = 75$ Hz, varies from hundreds to thousands km.

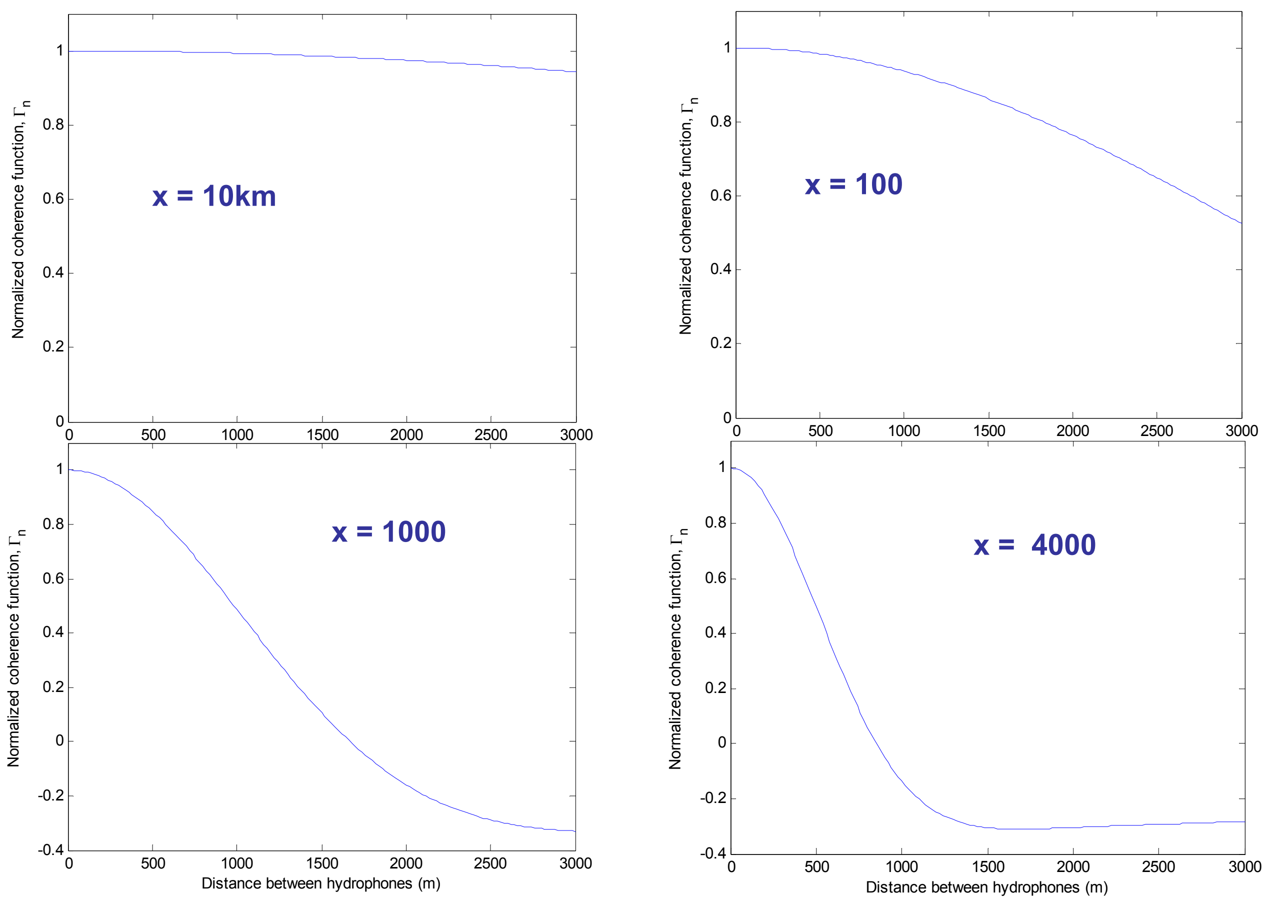

Figure 3. The normalized coherence function versus the distance between hydrophones y for the 10th mode and different values of the sound propagation distance x.

IMPACT/APPLICATIONS

A new, modal, 3D theory of low-frequency, long-range sound propagation through a fluctuating ocean was developed. The theory provides equations for the first two statistical moments of a sound field. These statistical moments are important for better understanding of low-frequency, long-range sound propagation in a fluctuating ocean. They have been or will be compared with the statistical moments of a sound filed obtained in 1998-1999 and 2004-2005 NPAL experiments.

RELATED PROEJCTS

The related projects are:

(1) The 2004-2005 NPAL experiment, which is described in [2].

(2) The 1998-1999 NPAL experiment, see [1].

(3) "Multiple Scattering of Sound by Internal Waves and Acoustic Characterization of Internal Wave Fields in Deep and Shallow Water", ONR project N0001405IP20024.

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